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An Analytical Vacuum-Assisted Resin Transfer Molding (VARTM) Flow Model

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ARL-TR-2354 October 2000

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5069

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Abstract

A closed form solution for the flow of resin in the vacuum-assisted resin transfer molding (VARTM) process is used extensively for affordable manufacturing of large composite structures. During VARTM processing, a highly permeable distribution medium is incorporated into the preform as a surface layer. During infusion, the resin flows preferentially across the surface, simultaneously through the preform, to a complex flow front. The analytical solution presented here provides insight into the scaling laws governing fill times and resin inlet placement as a function of the properties of the preform, distribution media, and resin. The formulation assumes that the flow is fully developed and is divided into two areas: (1) a saturated region with no crossflow, and (2) a flow front region, which moves with a uniform velocity, where the resin is infiltrating into the preform from the distribution medium. The law of conservation of mass and Darcy's Law for flow through porous media are applied in each region. The resulting equations are nondimensionalized and are solved to yield the flow front shape and the development of the saturated region. It is found that the flow front is parabolic in shape, and the length of the saturated region is proportional to the square root of the time elapsed. The obtained results are compared to data from full-scale simulation and show good agreement. The solution allows greater insight into the physics process, enables parametric and optimization studies, and can reduce the computational cost of full-scale, three-dimensional (3-D) simulations.

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1. Introduction

The vacuum-assisted resin transfer molding (VARTM) process offers numerous cost advantages over traditional RTM via lower tooling costs, room temperature processing, and scalability to large structures. Recent advanced technology demonstrators such as the Advanced Enclosed Mast Sensor (AEM/S) System and the composite advanced vehicle (CAV) have shown the potential of VARTM technology for the low-cost fabrication of large-scale structures requiring thick-section construction and hybrid multifunctional integral armor. The VARTM process is also used extensively in commercial applications such as bridge decks, rail cars, and yachts (Figure 1).

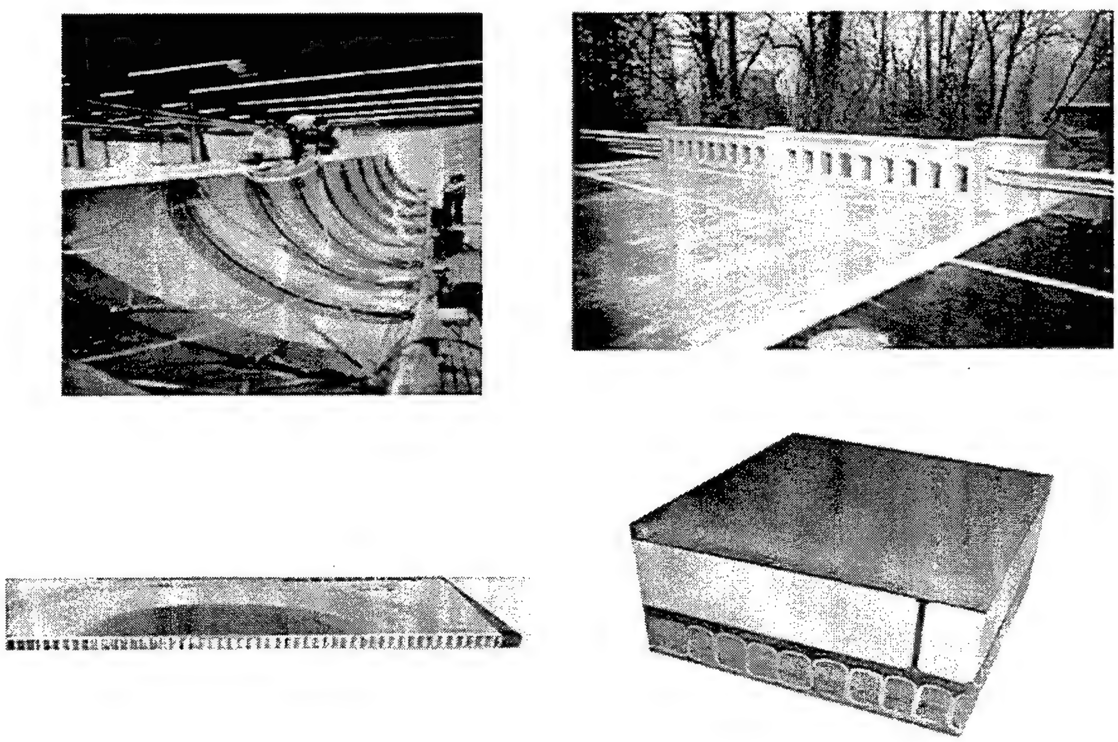


Figure 1. Examples of the Broad Application Potential for VARTM Processes Including Shipping, Infrastructure, Land Combat Vehicle Armor, and Repair.

VARTM is a composites manufacturing process that involves the layup and vacuum bagging of dry reinforcing fibers in fabric, tape, or bulk form as a preform in a one-sided open mold and impregnating the preform with liquid resin using negative pressure (i.e., a vacuum) followed by cure and demolding. The advantages of the VARTM process over the RTM process are scalability and affordability for the fabrication of large composite structures. Large parts can be infused rapidly using vinyl esters, phenolics, and epoxies at room temperature under vacuum pressure only. Consequently, tooling costs and investments are substantially reduced. VARTM is a completely closed system that traps volatile organic compounds (VOCs), reduces the need for solvents, and results in less scrap than other processes.

The present study focuses on Seemann's Resin Infusion Molding Process (SCRIMP) (Seemann 1990). In this VARTM process, a highly permeable distribution medium is incorporated into preform as a surface layer. During infusion, the resin flows preferentially across the surface and simultaneously through the preform thickness enabling large parts to be fabricated solely under vacuum pressure. The layup of the materials in the process is shown in Figure 2.

In very large composite structures, multiple inlet gates are required to ensure complete wet-out of the part prior to gelation of the resin. Selection of distribution media, performs, and gate and vent locations are based on past experience for similar applications. New applications in which part thickness, resin, or preform characteristics change require costly trial and error process development. Hence, a fundamental understanding of the process physics and associated models represent a significant contribution to the science base for VARTM.

Modeling and predicting the flow during the impregnation process provides insight into the process physics and highlights potential problems before production. In addition, flow prediction enables optimization of the design variables affecting the process, such as the distance between resin inlets (in the case of multiple lines and thickness of the diffusion layer), and provides rules of thumb for scaling of the prototypes. Thus, a fundamental understanding of the underlying science will help develop models to reduce costs, aid in selection of design parameters, and improve quality.

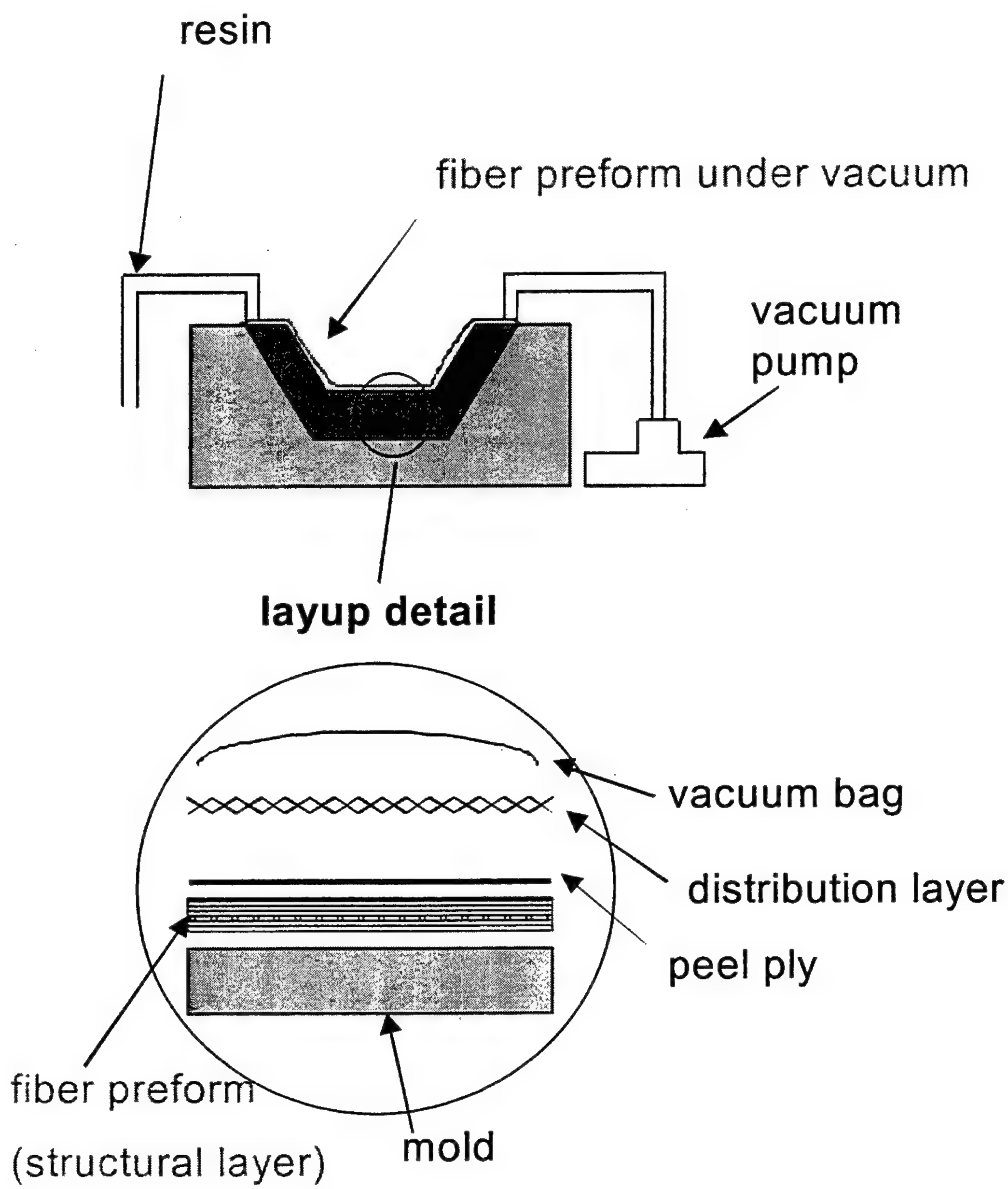


Figure 2. Layup of Materials in the VARTM Process.

The flow of resin through porous media such as fiber preforms and resin distribution media is governed by Darcy's Law:

$$u = \frac{-K}{\mu}.\nabla P, \tag{1}$$

where u is the Darcy's velocity (defined as the total flow rate per total flow front area), K is the permeability tensor (which characterizes the ease of flow through the fiber perform), and μ is the viscosity of the resin. This, when coupled with the continuity equation for incompressible flow, gives the Laplace equation for the fluid pressure field inside a region permeated by the fluid:

$$\nabla \cdot \left(\frac{K}{\mu} . \nabla P \right) = 0. \tag{2}$$

This equation can be discretized using finite element methods which then form the basis for simulation of mold-filling during the resin infusion process (Bruschke and Advani 1990, 1991a; Liu et al. 1996; Mohan et al. 1999).

The flow simulations can be either two-dimensional (2-D) or three-dimensional (3-D). In 2-D flow modeling (Bruschke and Advani 1991b; Trochu et al. 1994; Lee et al. 1994), the flow of resin through the thickness is considered uniform, and the finite element discretization is applied along the other two directions as with liquid injection molding simulation (LIMS), which is based on the finite element/control volume approach. In 2-D simulations, only the in-plane permeabilities are supplied (Simacek et al. 1998). In 3-D simulations, the pressure and flow in all three directions is solved, and a 3-D permeability sensor is supplied as input, as in the resin infusion process simulation (RIPS), which is based on finite element methods without the use of the control volume approach (Gallez and Advani 1996). Usually, the geometry, the material parameters, and the position of resin inlets and outlets are specified before the filling simulation is carried out. Simulation codes are used to track flow fronts and estimate the fill times.

Parametric studies then can be conducted with simulations to design the mold and the process parameters.

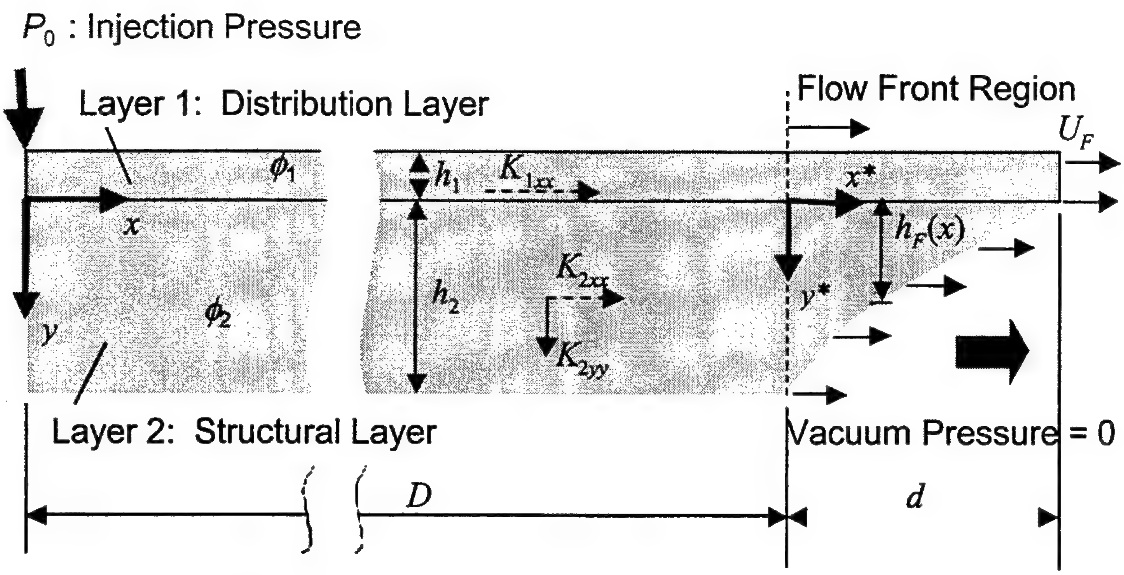
Closed form analytical solutions have also been derived for the resin flow under simplifying assumptions and for simple geometries. These solutions explain the role of various process variables and their interactions during processing. Indeed, a closed form solution of the resin flow during the VARTM process not only enables parametric studies, optimization, and reduction of computational expenses of full-scale simulations, but also offers insight on the scaleup of the process and material parameters for large structures.

In earlier work, Tari et al. (1998) derived a closed form model for vacuum-bag RTM under several simplifying assumptions. They assumed that the velocity of resin in the fiber preform is negligible and that the region behind the flow front is uniformly saturated. In the present work, these assumptions were not made, so the velocity of the resin, as well as the shape of the flow front through the thickness of the fiber perform, are accurately captured. This is important for scaling purposes.

A closed form solution for the flow of resin in the VARTM process is presented here. The layup is modeled as the distribution layer (high permeability material) and the structural layer (preform material). It is assumed that the flow is well developed and can be divided into a saturated region with no crossflow and a flow front region in which the resin infiltrates the preform from the distribution medium. The flow front region is assumed to be fully developed with a uniform velocity. The law of conservation of mass and Darcy's Law for flow through porous media are applied in each region. The resulting equations are nondimensionalized and are solved to yield the flow front shape and the development of the saturated region.

2. Problem Statement

As illustrated in Figure 3, the layup of materials is modeled as two layers of permeable materials. The distribution layer is much thinner than the structural layer, $h_1 << h_2$, where h_1 and



Note: d - region with transverse flow = flow front length.
D - region without transverse flow = length behind the flow front region.
U_F - flow front velocity.
μ - viscosity of resin.

Figure 3. Two-Layer Model of Resin Flow in the VARTM Process.

h_2 are the respective thicknesses of the two layers. The flow front in the distribution layer is considered uniform. The permeability of the distribution layer is K_{1xx} along the flow direction, and the permeabilities of the structural layer are K_{2xx} and K_{2yy} in the x and y directions, respectively. The constant inlet injection pressure (atmospheric pressure) is P_0, and the resin viscosity is μ.

In the saturated region, the flow is one-dimensional (1-D) with Darcy's velocities U_1 and U_2 in layers 1 and 2, respectively. The length of this saturated region is *D*, and the pressure at its boundary with the second flow region is assumed to be P_D.

The second region, illustrated in Figure 4, is the flow front region where there is transverse flow from the distribution layer to the structural layer. The flow front region of length *d* is assumed to maintain its shape, given by h_F, and advances with a uniform horizontal velocity of

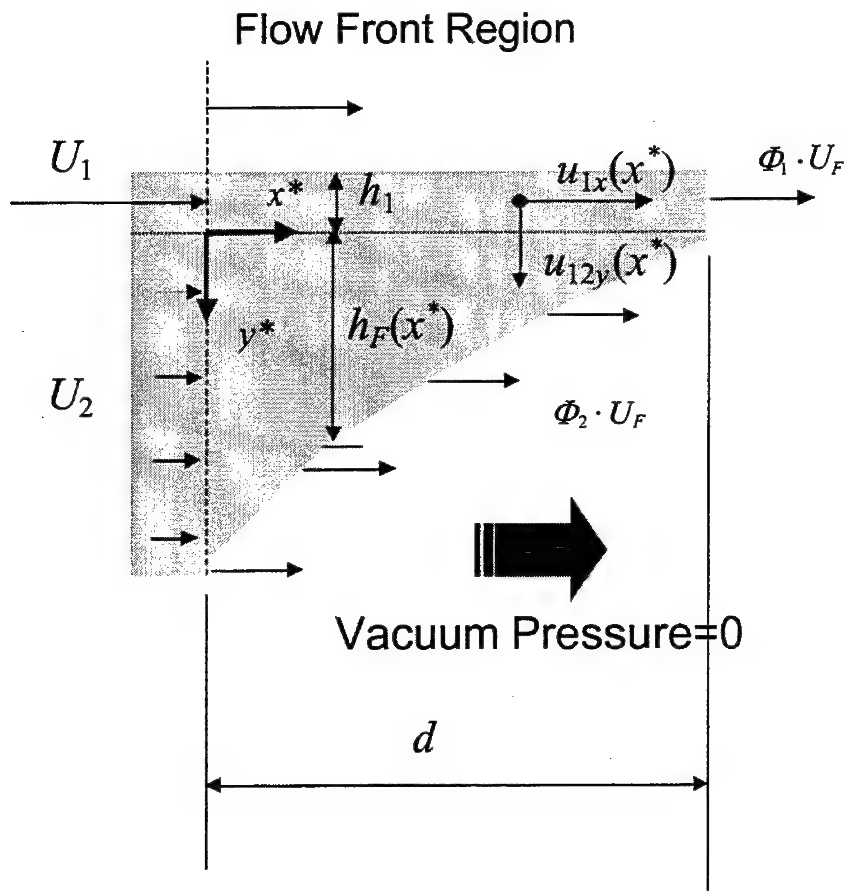


Figure 4. Schematic of Resin Flow in the Flow Front Region for the Two-Layer VARTM Model.

U_F. This is the observed velocity of the resin and not the Darcy's velocity. The transverse velocity of resin infiltration from the distribution layer into the structural layer is u_{12y}. The horizontal velocity in the flow front region in the distribution layer u_{1x} is with boundary condition $u_{1x}(x = D + d) = \Phi_1 U_F$.

Since the resin is an incompressible fluid, using the continuity equation and Darcy's Law in the structural layer, the governing equation for the pressure distribution is

$$K_{2xx}\frac{\partial^2 P}{\partial x^2}+K_{2yy}\frac{\partial^2 P}{\partial y^2}=0. \tag{3}$$

Consider the following nondimensional variables:

$$P^*=\frac{P}{P_c},x^*=\frac{x}{x_c},y^*=\frac{y}{y_c}, \tag{4}$$

where x_c and y_c are the characteristic length scales in the longitudinal and thickness directions, respectively, and P_c is a scaling parameter for the pressure. Introducing the dimensionless variables, the governing equation can be recast in dimensionless form as follows (Pillai and Advani 1998a, 1998b):

$$\frac{K_{2xx}y_c^2}{K_{2yy}x_c^2}\frac{\partial^2 P^*}{\partial x^{*2}}+\frac{\partial^2 P^*}{\partial y^{*2}}=0. \tag{5}$$

Since the resin distribution media was used in the process to enable the rapid and uniform distribution of the resin across the mold surface, it can be assumed that within the flow front region in the structural layer, the major portion of the resin flow is from the distribution layer into the structural layer. Hence, the flow rate in the y direction must be more significant than that in the x direction (i.e., $Q_y >> Q_x$). The x_c in the flow front region is d, while y_c is h_2. If $\bar{u}$ and $\bar{v}$ are the average Darcy's velocities in the two directions, then

$$Q_y=\bar{v}d,$$

and (6)

$$Q_x=\bar{u}h_2.$$

Considering Darcy's equation for the velocities, the following scaling argument can be made:

$$u = -\frac{K_{2xx}}{\mu}\frac{\partial P}{\partial x} \Rightarrow \bar{u} \sim \frac{K_{2xx}}{\mu}\frac{P_c}{d}\ , \tag{7}$$

and

$$v = -\frac{K_{2yy}}{\mu}\frac{\partial P}{\partial y} \Rightarrow \bar{v} \sim \frac{K_{2yy}}{\mu}\frac{P_c}{h_2}. \tag{8}$$

Since $Q_y >> Q_x$, from equations 6 to 8, it can be determined that:

$$\frac{K_{2xx}h_2^2}{K_{2yy}d^2} << 1. \tag{9}$$

This allows for the neglect of the x-term in pressure equation 5 in the flow front region, which leads to the following result:

$$\frac{\partial^2 P}{\partial y^2} = 0 \Rightarrow \frac{\partial P}{\partial y} = f_F(x),$$

and (10)

$$v = -\frac{K_{2yy}}{\mu}\frac{\partial P}{\partial y} = -\frac{K_{2yy}}{\mu} f_F(x).$$

At the top of the structural layer, where the flow is always from the distribution layer, the boundary condition is defined as $v\,|_{y=0} = u_{12y}(x)$. Hence, in the flow front region,

$$v(x) = u_{12y}(x)\,,$$

where $u_{12y}(x)$ is the velocity of the resin flow from the distribution to the structural layer in the flow front region. In the saturated region, the length scale of the flow is D in the x direction and h_2 in the y direction, where $D >> h_2$. Since $D >> d$, from equation 9,

$$\frac{K_{2xx} h_2^2}{K_{2yy} d^2} << 1 \Rightarrow \frac{K_{2xx} h_2^2}{K_{2yy} D^2} << 1. \quad (11)$$

So, the first term in equation 5 can be neglected, and

$$\frac{\partial^2 P}{\partial y^2} = 0 \Rightarrow \frac{\partial P}{\partial y} = fs(x). \quad (12)$$

Thus, the velocity in the y direction in the saturated region is

$$v = -\frac{K_{2yy}}{\mu}\frac{\partial P}{\partial y} = -\frac{K_{2yy}}{\mu} f_S(x). \quad (13)$$

At the bottom of the structural layer in the saturated region, the resin is in contact with the surface of the mold, which is impermeable. Hence, the no-penetration boundary condition was applied (i.e., $v = 0 \,@ y = h_2$) in the saturated region. Therefore,

$$\frac{\partial P}{\partial y} = f_S(x) = 0 \text{ in the saturated region.} \quad (14)$$

As a result, v = 0 in the saturated region everywhere in the structural layer. Since v = 0, the second term in pressure equation 3 becomes zero, and

$$\frac{\partial^2 P}{\partial x^2} = 0 \Rightarrow \frac{\partial P}{\partial x} = g(y),$$

as

$$\frac{\partial P}{\partial y} = 0.$$

So, it can be inferred that $g(y)$ is constant, and

$$u = -\frac{K_{2xx}}{\mu}\frac{\partial P}{\partial x} \tag{15}$$

is constant in the saturated region. Hence, from boundary conditions of $P = P_0\ @x = 0$ and $P = P_D\ @x = D$,

$$\frac{\partial P}{\partial x} = \frac{P_D - P_0}{D} \text{ in the saturated region.} \tag{16}$$

3. Analytical Solution

Considering the element fluid volumes shown in Figure 5 and invoking the mass balance,

$$u_{12y}dx + U_2(-dh_F) = U_F\Phi_2(-dh_F) \Rightarrow u_{12y} = \frac{-dh_F}{dx}(\Phi_2 U_F - U_2). \tag{17}$$

A lumped mass balance in the distribution layer in the flow front region gives

$$-du_{1x}h_1 = u_{12y}dx \Rightarrow u_{12y} = -h_1\frac{du_{1x}}{dx}. \tag{18}$$

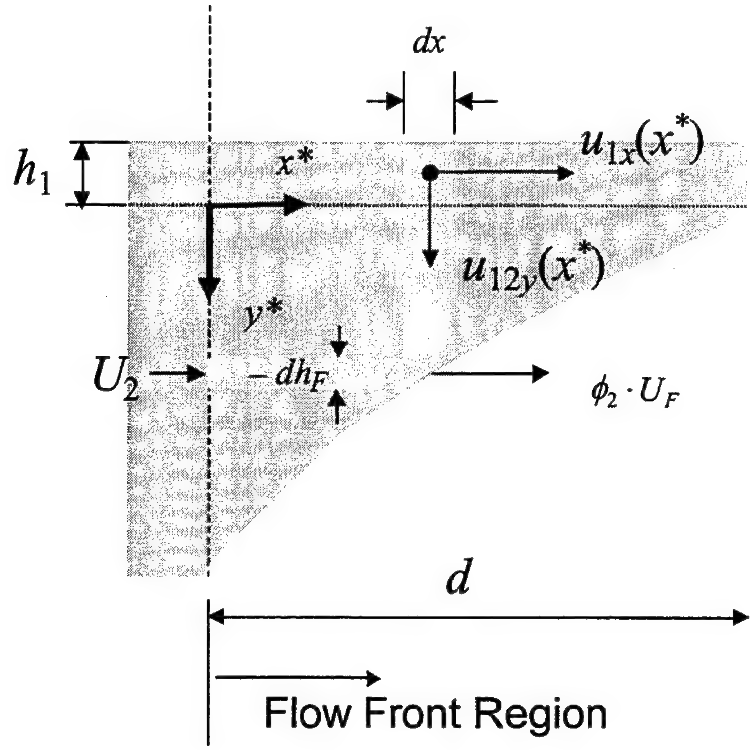


Figure 5. Illustration for Resin Mass Balance in the Flow Front Region in the Two-Layer Model.

From equations 17 and 18, the result is

$$u_{12y} = -h_1 \frac{du_{1x}}{dx} = \frac{-dh_F}{dx}(\Phi_2 U_F - U_2). \tag{19}$$

Applying Darcy's Law in the y direction in the flow front region and using equations 17 and 18,

$$u_{12y} = \frac{K_{2yy}}{\mu} \frac{P_1 - 0}{h_F},$$

and

$$u_{12Y} = -h_1 \frac{du_{1x}}{dx} = \frac{-dh_F}{dx}(\Phi_2 U_F - U_2) = \frac{K_{2yy}}{\mu} \frac{P_1}{h_F}. \tag{20}$$

This leads to the following equation for $P_1(x^*)$, the pressure field in the distribution medium in the flow front region:

$$P_1\left(x^*\right) = -h_F \frac{dh_F}{dx}\left(\Phi_2 U_F - U_2\right)\frac{\mu}{K_{2yy}}. \tag{21}$$

A similar mass balance in the flow front region, including both the structural and the distribution layers, yields

$$U_1 h_1 + U_2 h_2 = U_F\left(\Phi_1 h_1 + \Phi_2 h_2\right). \tag{22}$$

Applying Darcy's Law in the saturated region with 1-D flow,

$$U_1 = \frac{K_{1xx}}{\mu}\frac{P_0 - P_D}{D},$$

and (23)

$$U_2 = \frac{K_{2xx}}{\mu}\frac{P_0 - P_D}{D} \Rightarrow U_1 = U_2 \frac{K_{1xx}}{K_{2xx}}.$$

In combination with equation 22,

$$\frac{U_2}{U_F} = \frac{\left(\Phi_1 h_1 + \Phi_2 h_2\right)}{\left(\dfrac{K_{1xx}}{K_{2xx}} h_1 + h_2\right)}. \tag{24}$$

The previous set of equations can be nondimensionalized using the following nondimensional variables:

$$U^* = \frac{U}{U_F}, K^* = \frac{K}{K_{1xx}},$$

$$h_F^* = \frac{h_F}{h_2}, x^* = \frac{x-D}{h_2}, \tag{25}$$

and

$$h_1^* = \frac{h_1}{h_2}, d^* = \frac{d}{h_2}, P^* = \frac{P}{P_0}.$$

This gives the following system of equations:

$$u_{1x}^* = \frac{-1}{\mu^*}\frac{dP_1^*}{dx^*}, \tag{26}$$

$$U_2^* = \frac{\left(\phi_1 h_1^* + \phi_2\right)}{\left(\frac{h}{K_{1xx}^*} + 1\right)}, \tag{27}$$

$$\frac{du_{1x}^*}{dx^*} = \frac{\left(\phi_2 - U_2^*\right)}{h_1^*}\frac{dh_F^*}{dx^*}, \tag{28}$$

and

$$P_1^* = -h_F^* \frac{dh_F^*}{dx^*}\left(\phi_2 - U_2^*\right)\frac{\mu^*}{K_{2yy}^*}. \tag{29}$$

Here, $\mu^* = \frac{\mu h_2 U_F}{K_{1xx} P_0}$ is obtained from the nondimensional Darcy's Law. The boundary conditions

on u_{1x}^* are $u_{1x}^*(0)=U_1^*, u_{1x}^*(d^*)=\phi_1$. The boundary conditions on $h_F^*(0)=1, h_F^*(d^*)=0$. The pressure boundary conditions are $P_1^*(0)=P_D^*, P_1^*(d^*)=0$.

Integrating equation 29 and applying the boundary condition $u_{1x}^*(0)=U_1^*, u_{1x}^*(d^*)=\Phi_1$,

$$u_{1x}^* = \frac{(\phi_2 - U_2^*)}{h_1^*} h_F^*(x^*) + \Phi_1. \tag{30}$$

In combination with equation 26,

$$\frac{dP_1^*}{dx^*} = -\mu^* u_{1x}^* = \mu^* \left[\frac{(\phi_2 - U_2^*)}{h_1^*} h_F^*(x^*) + \Phi_1 \right]. \tag{31}$$

Combining equations 29 and 31, the following nonlinear ODE with boundary conditions $h_F^*(0)=1, h_F^*(d^*)=0$ result in:

$$\frac{d}{dx^*}\left(h_F^* \frac{dh_F^*}{dx^*} \right) = \frac{K_{2yy}^*}{h_1^*} h_F^*(x^*) + \frac{\Phi_1 K_{2yy}^*}{\Phi_2 - U_2^*}. \tag{32}$$

This ODE is of the form given by $(y^2)'' = ay + b$. It can be solved using the substitution $p = \frac{dy}{dx}, y'' = p\frac{dp}{dy}$ (Murphy 1960). This usually yields a solution in a quadratic form. The quadratic form $h_F^*(x^*) = \alpha x^{*2} + \beta x^* + \gamma$ can be substituted into the above equation to find the solution using the first boundary condition $h_F^*(0)=1$ and matching the coefficients of the powers of x^* on either side. Then the second boundary condition, $h_F^*(d^*)=0$, can be used to determine d^*. This gives a quadratic equation for d^* having two roots. Both roots are positive, but if the larger one were chosen, then the flow front profile would be physically impossible (Figure 6). Hence, the smaller root gives the following unique solution:

$$\alpha = \frac{K^*_{2yy}}{6h^*_1},$$

$$\beta = -\sqrt{\frac{2K^*_{2yy}}{3h^*_1} + \frac{\Phi_1 K^*_{2yy}}{\Phi_2 - U^*_2}}, \tag{33}$$

and

$$\gamma = 1.$$

Thus,

$$h^*_F(x^*) = \frac{K^*_{2yy}}{6h^*_1} x^{*2} - \sqrt{\frac{2K^*_{2yy}}{3h^*_1} + \frac{\Phi_1 K^*_{2yy}}{\Phi_2 - U^*_2}}\, x^* + 1, \tag{34}$$

and since $h^*_F(d^*) = 0, d^*$ can be determined as

$$d^* = \frac{3h^*_1}{\sqrt{K^*_{2yy}}} \left(\sqrt{\frac{\Phi_1}{\Phi_2 - U^*_2} + \frac{2}{3h^*_1}} - \sqrt{\frac{\Phi_1}{\Phi_2 - U^*_2}} \right). \tag{35}$$

Substituting the form $h^*_F(x^*) = ax^{*2} + \beta\chi^* + \gamma$ in equation 29, the pressure can be determined as follows:

$$P^*_1 = -\frac{(\Phi_2 - U^*_2)\mu^*}{K^*_{2yy}} \left[2\alpha x^{*3} + 3\alpha\beta x^{*2} + (\beta^2 + 2\alpha)x^* + \beta\right]. \tag{36}$$

Applying the boundary condition $P^*_1(0) = P^*_D$ gives

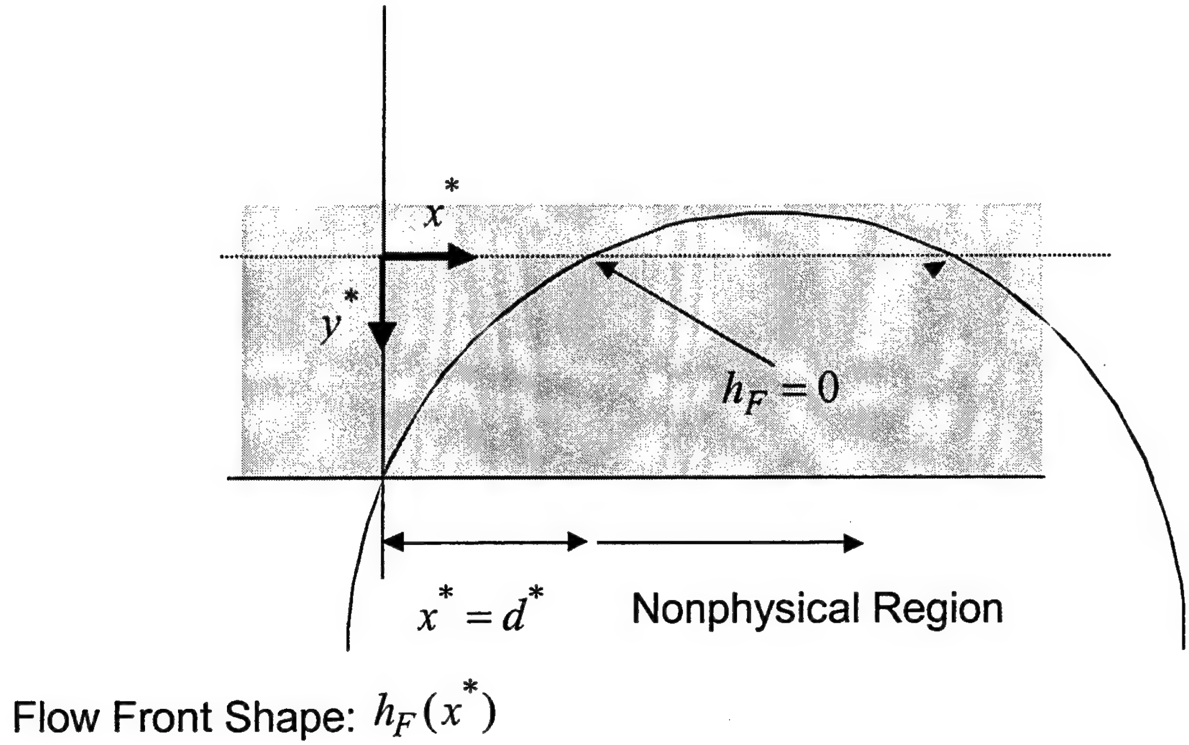


Figure 6. Two Mathematical Roots of $h_F{}^*(x^*) = 0$. Note That Only the Smaller Root Is Physically Possible.

$$P_D^* = -\frac{(\Phi_2 - U_2^*)\mu^*}{K_{2yy}^*}\beta = \frac{(\Phi_2 - U_2^*)\mu^*}{K_{2yy}^*}\sqrt{\frac{2K_{2yy}^*}{3h_1^*} + \frac{\Phi_1 K_{2yy}^*}{\Phi_2 - U_2^*}} \quad . \tag{37}$$

Using the nondimensional form of Darcy's Equation in the saturated region,

$$U_2^* = \frac{K_{2xx}^*}{\mu^*}\frac{1 - P_D^*}{D^*} \Rightarrow U_2^* D^* \frac{\mu^*}{K_{2xx}^*} = 1 - \mu^* \frac{\Phi_2 - U_2^*}{K_{2yy}^*}\sqrt{\frac{2K_{2yy}^*}{3h_1^*} + \frac{\Phi_1 K_{2yy}^*}{\Phi_2 - U_2^*}} \quad .$$

To find U_F^* substituted with μ^* is

$$\mu^* = \frac{\mu h_2 U_F}{K_{1xx} P_0} = \frac{1}{\Gamma D^* + \Lambda} \quad , \tag{38}$$

where

$$\Gamma = \frac{U_2^*}{K_{2xx}^*}$$

and

$$\Lambda = \frac{\left(\Phi_2 - U_2^*\right)}{K_{2yy}^*}\sqrt{\frac{2K_{2yy}^*}{3h_1^*} + \frac{\Phi_1 K_{2yy}^*}{\Phi_2 - U_2^*}} \ . \tag{39}$$

From equation 38, the flow front velocity is

$$U_F = \frac{K_{1xx}P_0}{\mu h_2}\frac{1}{\Gamma D^* + \Lambda} \ , \tag{40}$$

but $U_F = \dfrac{dD}{dt}$, and $D^* = \dfrac{D}{h_2}$; hence, the previous equation becomes

$$\frac{dD}{dt} = \frac{K_{1xx}P_0}{\mu h_2}\frac{1}{\Gamma D + \Lambda\, h_2} \ . \tag{41}$$

Solving the resulting differential equation for *D*(*t*),

$$t - t_0 = C_1\left(D^2 - D_0^2\right) + C_2\left(D - D_0\right) \ , \tag{42}$$

where $C_1 = \dfrac{\Gamma\mu}{2K_{1xx}P_0}$ and $C_2 = \dfrac{\mu\Lambda\, h_2}{K_{1xx}P_0}$ The variable t_0 is the time it takes for the flow front region to become fully developed, while D_0 is the entry length for the development of the flow front region. Solving for *D*(*t*),

$$D(t) = \frac{\sqrt{(\Lambda h_2)^2 + \frac{\Gamma \mu}{2K_{1xx}P_0}\left(t - t_0 + C_1 D_o^2 + C_2 D_0\right)} - \Lambda h_2}{\Gamma} . \tag{43}$$

Equations 42 and 43 are important for the design of the VARTM process. The results obtained are compared to full-scale, finite-element-based simulations using LIMS 4.0 and are presented in the next section. A parametric study is presented to shed light on how one can scale the parameters in the VARTM process.

4. Verification: Full-Scale Simulations

The results obtained can be compared to finite-element-based simulations of the filling process in VARTM. LIMS 4.0 was used for simulation of the filling process for five different cases, with different values for permeabilities and fiber volume fractions for the distribution and structural layers, respectively, and length of part, D. Each part was modeled using finite elements and the filling process simulated as a constant pressure injection at 1 atm at one corner of the part. The viscosity of the resin, the thicknesses of the structural and distribution layers, and the permeability of the distribution layer were held constant. The fill times and the values of d were determined and compared to those obtained from the closed form solution. The results are tabulated in Table 1. The fill time from the analytical solution was found to be within 2% of the value from the full-scale numerical simulation, while the value of d was within 12% of the value from simulation. For all cases, the condition $\frac{K_{2xx}h_2^2}{K_{2yy}d^2} << 1$ was maintained for a valid analytical solution.

The flow front history and the pressure contours at the final time are plotted for Case 1 in Figure 7. It can be observed that the flow front is constant in shape, while the lines of constant pressure in the saturated region are equally spaced and vertical to the x axis, thus verifying the assumptions of constant flow front shape and linear variation in pressure in the saturated region.

Table 1. Comparison of Closed Form Solution With Results From Full-Scale Numerical Solution of the VARTM Process

Case	Parameters	d (cm)		t-t_0 (s)		% Error[a]	
		LIMS 4.0	Closed Form Solution	LIMS 4.0	Closed Form Solution	d (%)	t (%)
1	K_{2xx} = 8.8E-7 cm^2 K_{2yy} = 4.4E-7 cm^2 $\phi_1 = 0.99$, $\phi_2 = 0.50$ D-D_0 = 40.0 cm	8.9	9.8	44.9	44.8	9.7	-0.3
2	K_{2xx} = 8.8E-7 cm^2 K_{2yy} = 4.4E-8 cm^2 $\phi_1 = 0.99$, $\phi_2 = 0.50$ D-D_0 = 19.0 cm	29.2	30.9	19.1	19.4	5.7	1.5
3	K_{2xx} = 8.8E-7 cm^2 K_{2yy} = 4.4E-6 cm^2 $\phi_1 = 0.99$, $\phi_2 = 0.50$ D-D_0 = 47.0 cm	3.0	3.1	54.2	54.5	2.9	0.5
4	K_{2xx} = 8.8E-7 cm^2 K_{2yy} = 4.4E-7 cm^2 $\phi_1 = 0.99$, $\phi_2 = 0.80$ D-D_0 = 40.3 cm	9.2	10.1	71.7	72.1	10.2	0.6
5	K_{2xx} = 8.8E-7 cm^2 K_{2yy} = 4.4E-7 cm^2 $\phi_1 = 0.70$, $\phi_2 = 0.50$ D-D_0 = 40.0 cm	9.0	10.0	44.2	44.5	11.6	0.7

Note: The following variables were used in all cases:
P_0 = 1E6 g/cm-s^2,
μ = 1 g/cm-s
h_1 = 0.01 cm,
h_2 = 1 cm,
K_{1xx} = 1E-3 cm^2, and
D_0~0 cm for all the cases.
[a] Based on results from LIMS 4.0.

5. Effect of Process Variables: A Parametric Study

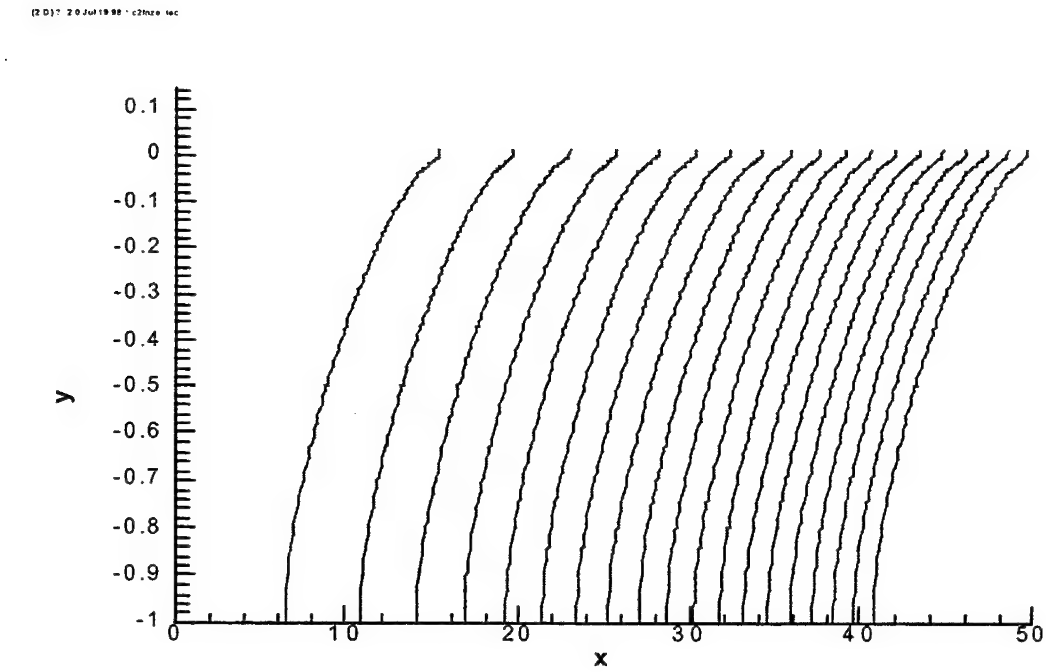
The process variables that affect the flow of resin are broadly classified into geometric parameters (such as thickness) and material properties (such as permeability and porosity of the two layers). These process variables influence the time to fill a mold of a given length. A parametric study of these effects allows for better design and analysis of the VARTM manufacturing process. In the present section, the effect of a number of process variables on the fill times and flow velocity was studied. The baseline values used for the study are:

$$\mathrm{P_0} = 1\ \mathrm{atm}, \mu = 1\ \mathrm{cp},$$
$$\mathrm{h_1} = 1.00\ \mathrm{cm}, \mathrm{h_2} = 0.025\ \mathrm{cm},$$
$$\mathrm{K_{1xx}} = 8.8\times10^{-4}\,\mathrm{cm}^2, \mathrm{K_{2xx}} = 8.8\times10^{-7}\,\mathrm{cm}^2, \mathrm{K_{2yy}} = 1.47\times10^{-7}\,\mathrm{cm}^2, \text{ and}$$
$$\Phi_1 = 0.99, \Phi_2 = 0.50.$$

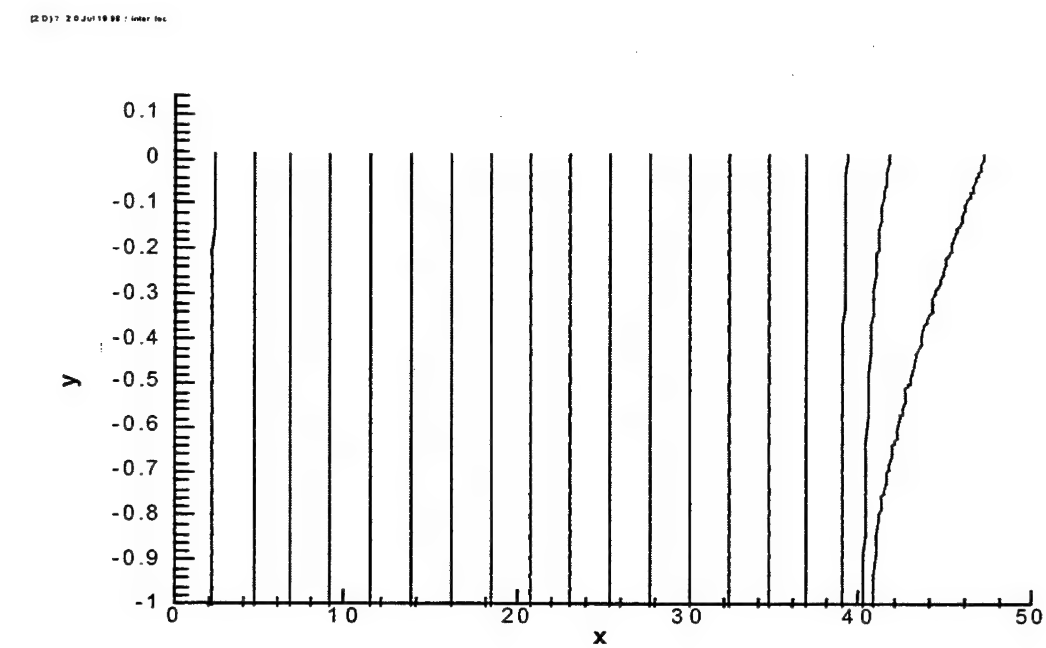
In the plots for each parameter, the flow front velocity (U_F) and the time taken (t) are plotted against D for different values of the parameter. Note that the time axis is reversed; therefore, the lines for t start from zero at the top of the graph.

5.1 Effect of Thickness Ratios. The effect of the ratio of the thickness of the distribution medium to that of the structural layer, $h_1^* = \frac{h_1}{h_2}$, is considered. Figure 8 plots the flow front velocity, U_F, vs. D for different thickness ratios. As h_1^* increases, the flow front velocity increases while the fill time decreases for a given length D. This is because as the thickness of the highly permeable distribution medium relative to that of the structural layer increases, the resin flow rate in the distribution medium increases. Since the diffusion material is used to distribute resin in the part and ensure mold filling, an increase in h_1^* will cause an increase in flow front velocity and a decrease in fill time.

For the case of $h_1^* = 0.1$, encountered with thin section composite parts, U_F shows a slower decrease with D than with the other cases. With thick-section composite parts where $h_1^* \to 0$,



(a) Flow Front History



(b) Pressure Distribution at the Final Time Step

Figure 7. Example of a Full-Scale Numerical Simulation: (a) Flow Front History and (b) Pressure Distribution at the Final Time Step.

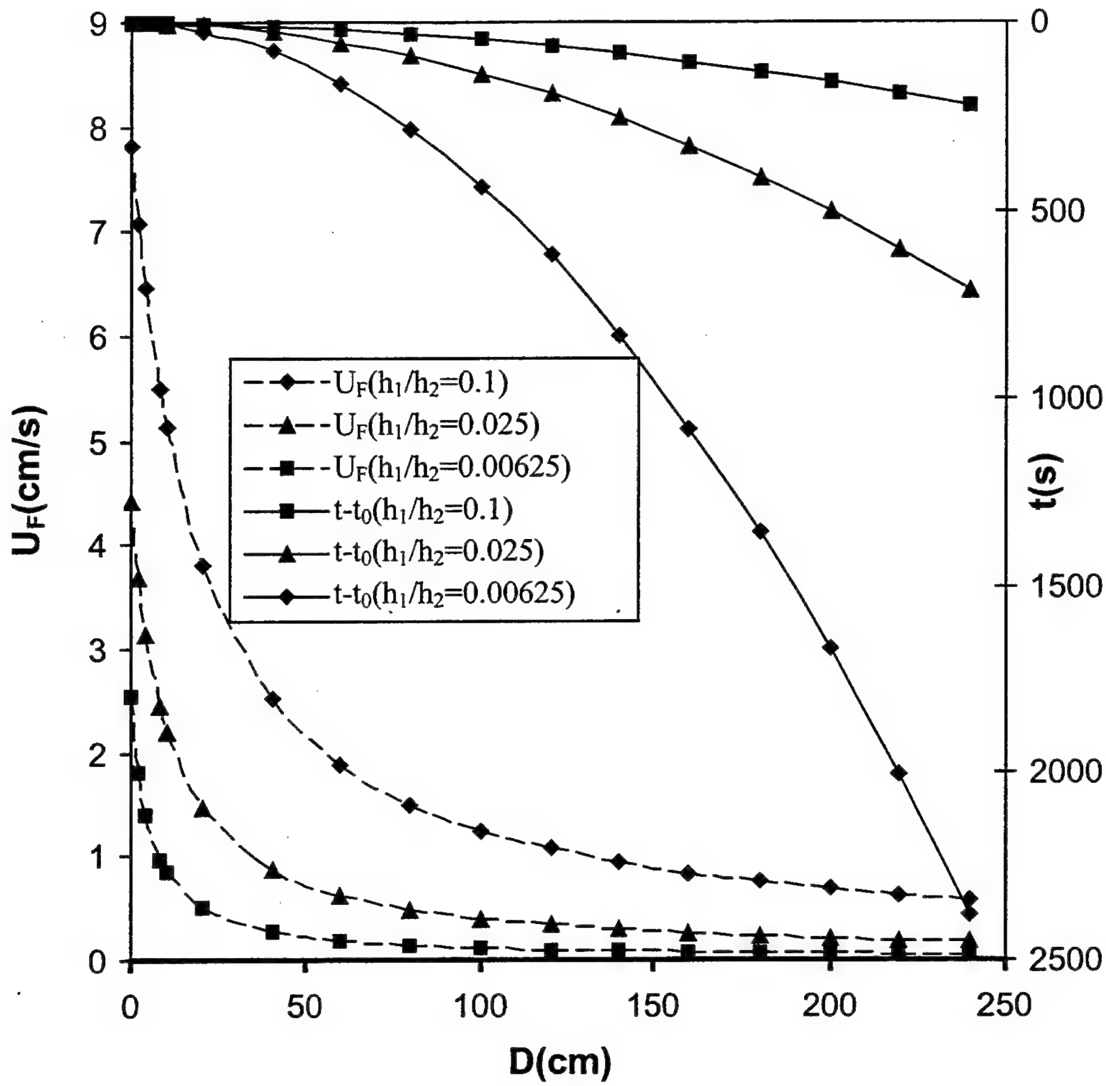


Figure 8. Flow Front Velocity and Fill Time as a Function of Length of the Saturated Region: Effect of Thickness Ratios.

U_F falls rapidly. In order to fill such a part efficiently, the distance between the gates (D) has to be small; thus, the number of gates required increases. Therefore, the solution provides insight into the scaling laws required for manufacturing thick-section composites by VARTM.

5.2 Effect of Permeability. The permeability values of importance are: K^*_{1xx}, the permeability of the distribution layer in the longitudinal x direction, and K^*_{2xx} and K^*_{2yy}, the permeabilities of the structural layer in the longitudinal x and thickness y directions. As seen in

Figures 9–11, as the permeability values increase, the time to fill decreases, and the flow front velocity increases. As the permeability values increase, the resistance of the material to the resin flow decreases. Hence, the net flow rates are higher, and the time to fill decreases, while the flow front velocity increases. Since the flow rate in the distribution layer is higher, the effect of K^*_{1xx} is significantly more than that of K^*_{2xx} and K^*_{2yy}. These effects can also be observed from the plots shown. This has important ramifications on the selection and the thickness of distribution media.

5.3 Effect of Porosity. The porosity of a fiber preform is defined as the fraction of the total volume of the material not occupied by the fibers. In composite manufacturing, the complementary term, volume fraction, was more commonly used. The volume fraction is defined as the fraction of the fiber preform occupied by the fibers and is related to the porosity by the relation $V_f = 1 - \Phi$. The porosity also affects the permeability of the material. However, this coupling has not been accounted for in the present work.

The porosity values considered here are Φ_1, the porosity of the distribution layer, and Φ_2, the porosity of the structural layer. As observed from Figure 12, Φ_1 did not significantly affect the time to fill and the flow front velocity. In Figure 13, as Φ_2 increases, the flow-front velocity decreases, and the fill time significantly increases. This is because the fraction of the total part volume occupied by the thin layer of diffusion material is very low compared to that occupied by the fiber preform in the structural layer. Hence, increasing the porosity of the diffusion material does not have a significant effect. Whereas, if Φ_2 increases, the volume of the structural layer (which is unoccupied by the fiber perform) significantly increases. This additional volume must be filled by the resin, thus requiring more time to fill it and therefore slowing down the flow front.

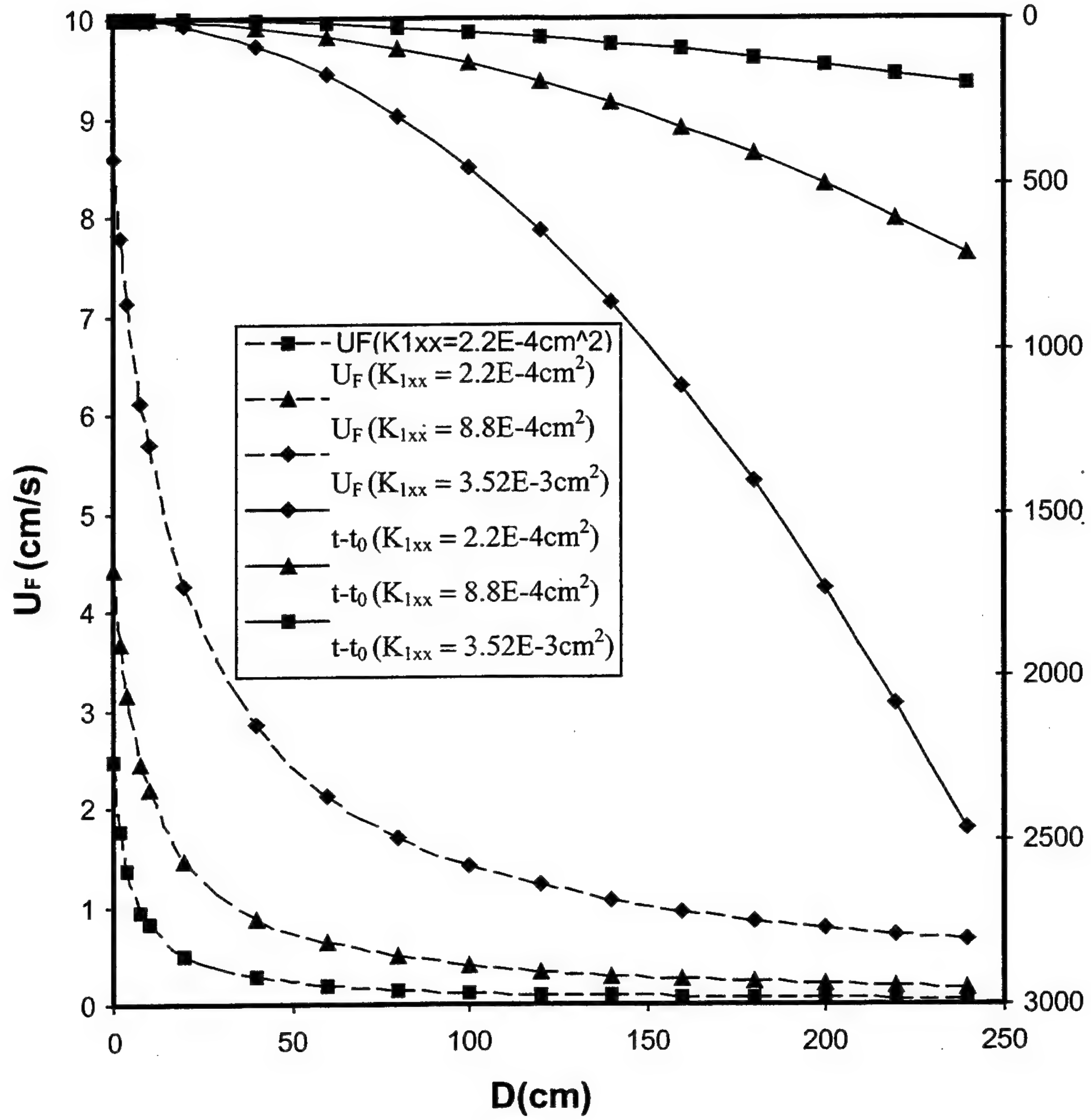


Figure 9. Flow Front Velocity and Fill Time as a Function of Length of the Saturated Region: Effect of Permeability of Distribution Medium.

6. Conclusions

A closed form solution for flow of resin in the VARTM process has been developed. This process is explained by a two-layer model comprised of a distribution layer and a structural layer, containing fiber preform. The flow is divided into a saturated region where there is no

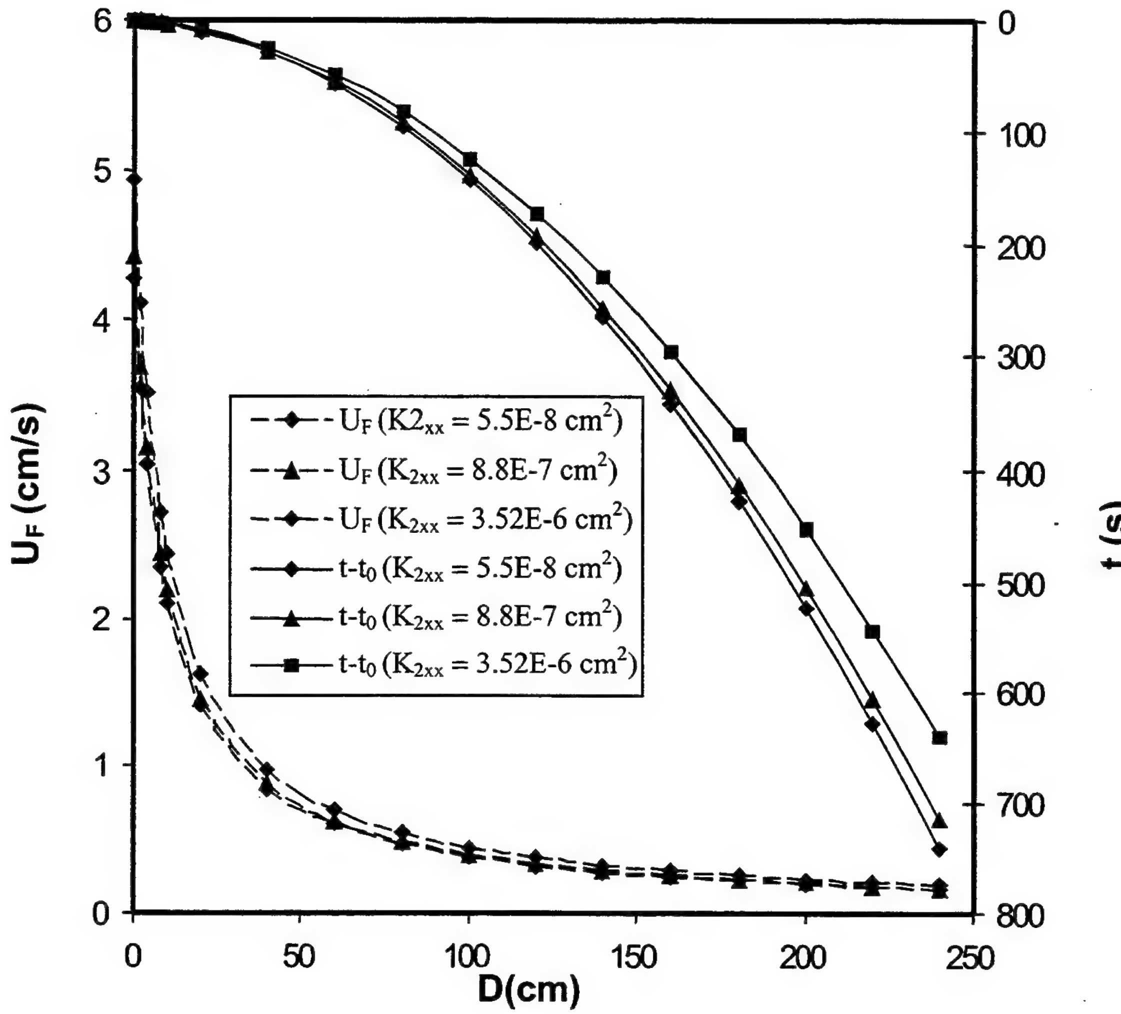


Figure 10. Flow Front Velocity and Fill Time as a Function of Length of the Saturated Region: Effect of In-Plane Permeability of Fiber Preform.

crossflow, and a flow front region with a steady shape and uniform velocity where the driving flow emanates from the distribution layer to the structural layer. It is assumed that the thickness of the distribution layer is much smaller than that of the structural layer, and that the length of the flow front region is much smaller than that of the saturated region. It is also assumed that the crossflow in the flow front region is much higher than the flow from the saturated region into the flow front region. Darcy's Law regarding flow in porous media and mass balances at different sections was used to formulate a system of differential equations, and a closed form solution was

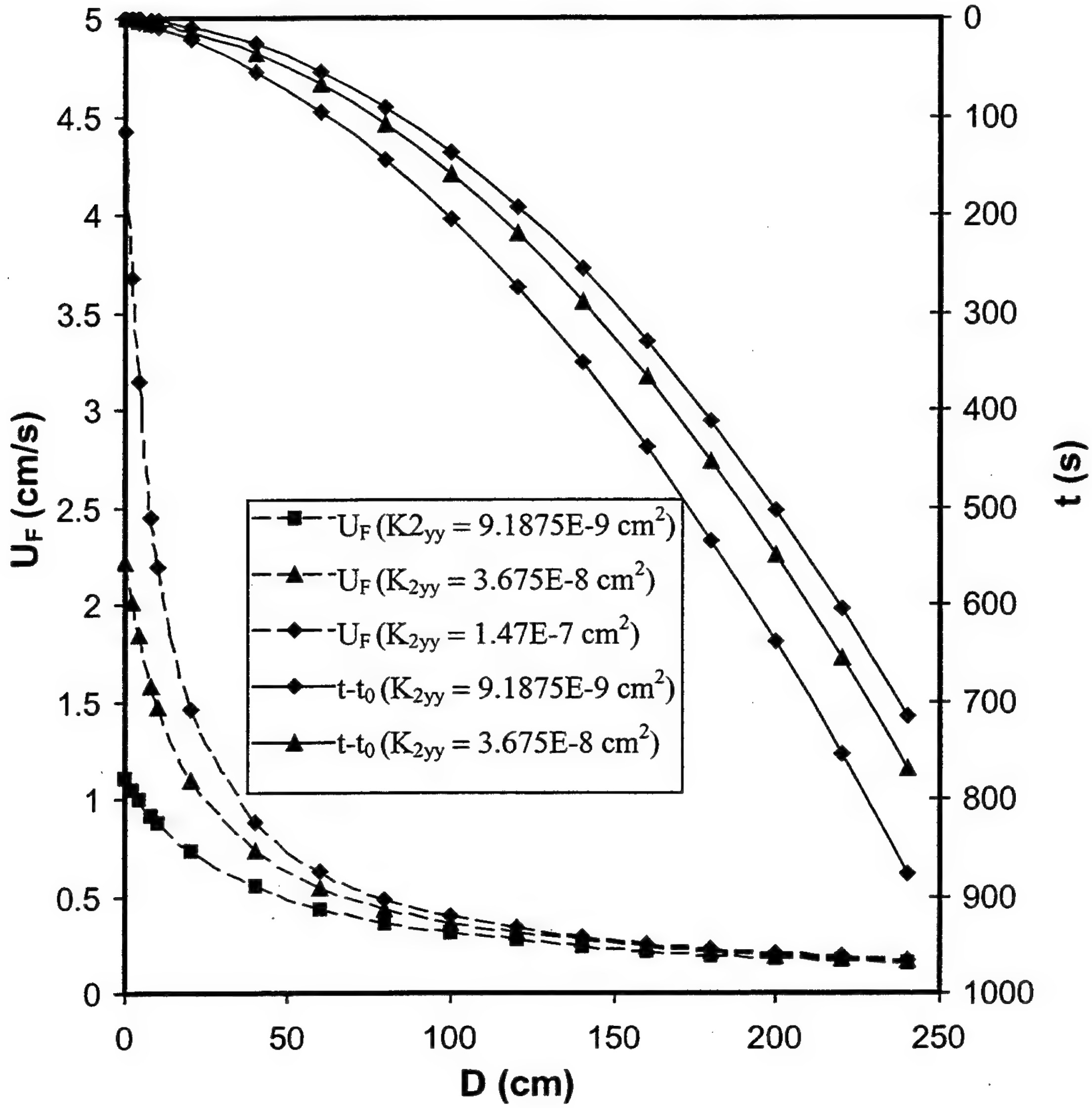


Figure 11. Flow Front Velocity and Fill Time as a Function of Length of the Saturated Region: Effect of Transverse Permeability of Fiber Preform.

found. The model predicted the shape and development of the flow front given the material properties, the geometric parameters, the pressure at the inlet, and the viscosity. The obtained results were verified by comparing them with full-scale simulations. The parametric study indicated trends that reflect the physics of the flow process and identified the parameters that

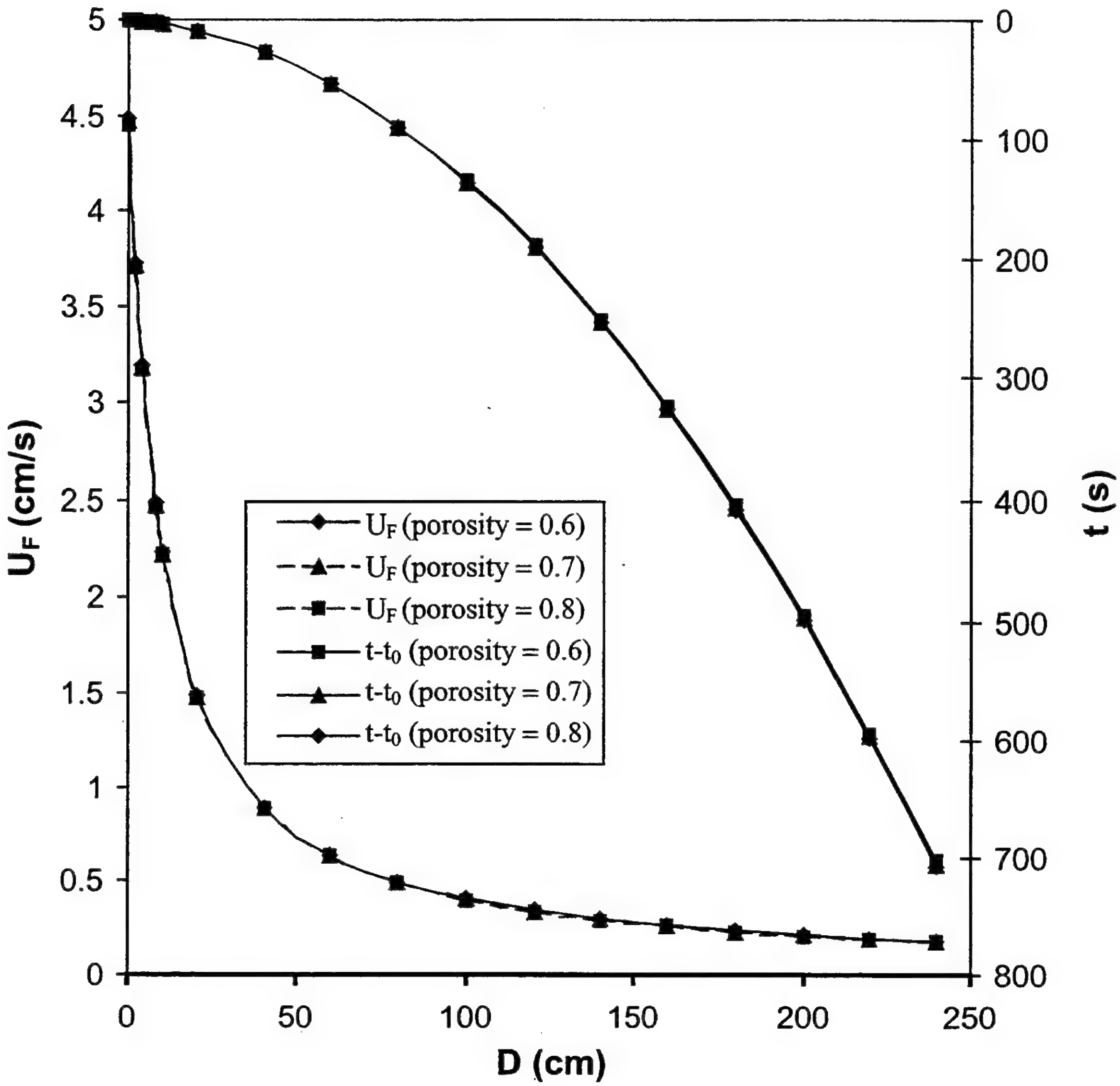


Figure 12. Flow Front Velocity and Fill Time as a Function of Length of the Saturated Region: Effect of Porosity of Distribution Medium.

significantly affect the filling process. Subsquent solutions provided physical insight into the manufacturing process and can be used for scaling, design, and optimization of the VARTM process.

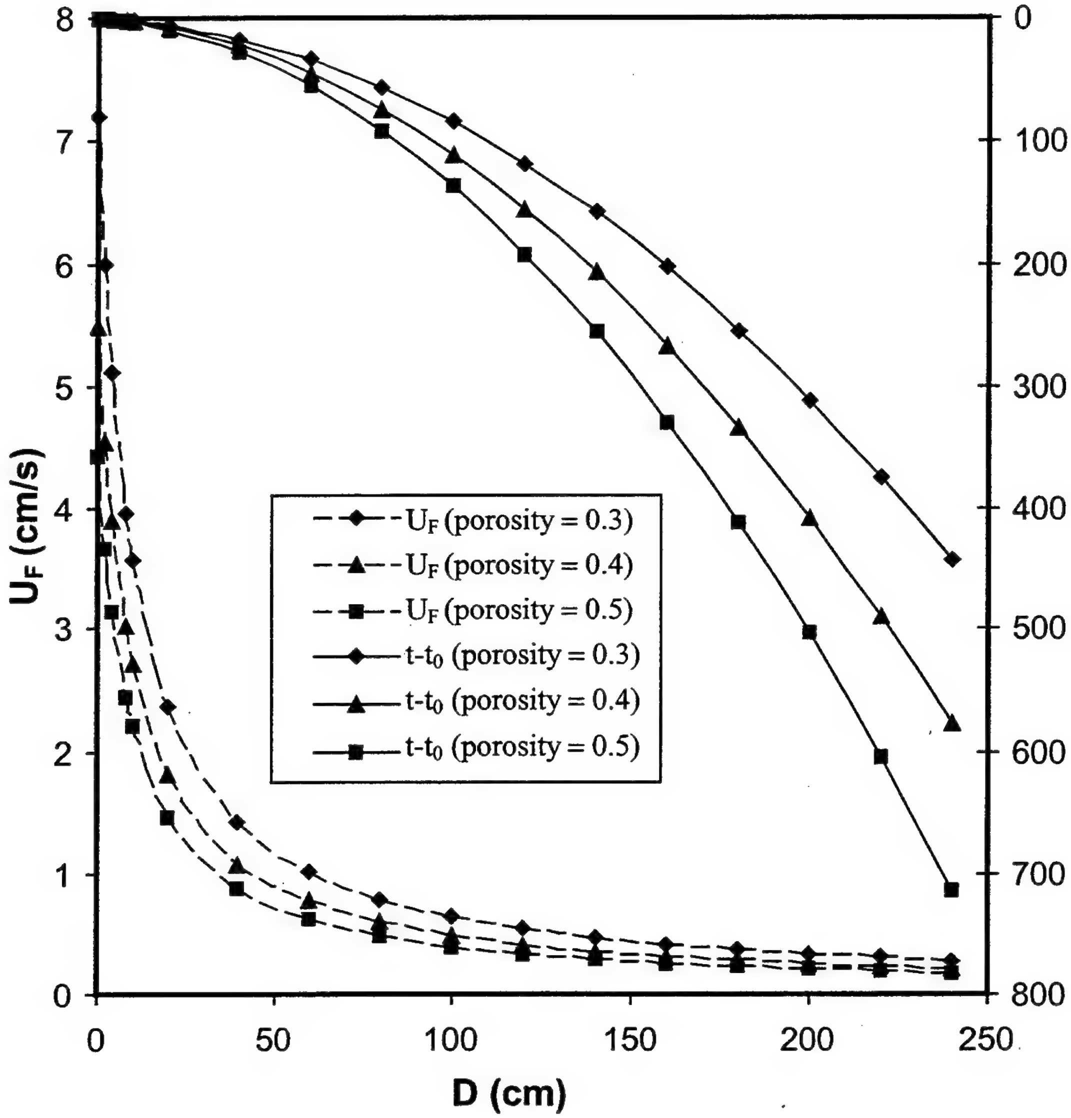


Figure 13. Flow Front Velocity and Fill Time as a Function of Length of the Saturated Region: Effect of Porosity of Fiber Preform.

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1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 2000	Final, January 1997–July 1999

4. TITLE AND SUBTITLE
An Analytical Vacuum-Assisted Resin Transfer Molding (VARTM) Flow Model

5. FUNDING NUMBERS
62105AH84

6. AUTHOR(S)
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Aberdeen Proving Ground, MD 21005-5069

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-2354

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

10.SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
* University of Delaware, Newark, DE 19716

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12b. DISTRIBUTION CODE

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A closed form solution for the flow of resin in the vacuum-assisted resin transfer molding (VARTM) process is used extensively for affordable manufacturing of large composite structures. During VARTM processing, a highly permeable distribution medium is incorporated into the preform as a surface layer. During infusion, the resin flows preferentially across the surface, simultaneously through the preform, to a complex flow front. The analytical solution presented here provides insight into the scaling laws governing fill times and resin inlet placement as a function of the properties of the preform, distribution media, and resin. The formulation assumes that the flow is fully developed and is divided into two areas: (1) a saturated region with no crossflow, and (2) a flow front region, which moves with a uniform velocity, where the resin is infiltrating into the preform from the distribution medium. The law of conservation of mass and Darcy's Law for flow through porous media are applied in each region. The resulting equations are nondimensionalized and are solved to yield the flow front shape and the development of the saturated region. It is found that the flow front is parabolic in shape, and the length of the saturated region is proportional to the square root of the time elapsed. The obtained results are compared to data from full-scale simulation and show good agreement. The solution allows greater insight into the physics process, enables parametric and optimization studies, and can reduce the computational cost of full-scale, three-dimensional (3-D) simulations.

14. SUBJECT TERMS
composite material, vacuum-assisted resin transfer molding, flow modeling

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

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